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DEVELOPMENT OF HYBRID SIMULATION SYSTEM WITH A GENERAL FEM SOFTWARE AND UI-SIMCOR AT COLD ENVIRONMENT

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Abstract

In these 20 years after Kobe Earthquake in Japan, seismic devices such as rubber bearing, seismic damper and other additional devices have been rapidly developed and they have been installed to bridges to improve their seismic performance. Seismic performance of bridges with seismic devices is commonly evaluated by numerical simulation. To establish numerical model of the bridge, the seismic device must be modeled properly. However stiffness and damping of such devices are nonlinear and their formulation needs many cases of loading tests and careful consideration for modeling. Moreover these devices often use materials which has thermal dependency, and it is concerned that these seismic performance deteriorates at winter season in cold region. Substructured hybrid simulation is effective for development of such devices with combination of numerical simulation and physical experiments. Whole of structures including steel and concrete members are modeled in numerical simulation with FEM software. Novel developed devices are tested simultaneously in loading facilities.

Therefore, a substructured hybrid simulation system for low-temperature environment was developed in this study. The developed system utilized an open-source pseudo-dynamic simulation system UI-SIMCOR and a sub-program which could cooperate with existent loading facility in a cold room was developed. The capacity of the loading facility was 300kN for static loading and it was able to operate in -30 degree in Celsius. To enhance usability of the system, another sub-program was also developed for application of general FEM software.

A simulation for a simple girder model with a seismic damper was performed. A girder model was consisted of 5 beam elements with supports at its ends. This girder was modeled by a general FEM software. A seismic device was connected to an intermediate node of the girder model. This seismic device was an experimental part of the hybrid simulation system. To confirm working the system properly, linear steel springs were installed instead of a seismic damper. Then after the pretest, a seismic damper was installed to evaluate seismic performance of the whole structure.

In the hybrid simulation, dynamic response of the damper was obtained as a part of whole structure and friction type displacement-force hysteresis curve was properly obtained. The maximum displacement was reduced 80% by energy dissipation of the damper. The result of the simulation was not affected by low temperature because the damper was stable to low temperature as shown in previous studies. Hence, the system was able to work properly as a substructured hybrid simulation facility at a low-temperature environment.

Keywords: Hybridge simulation; low-temperature environment; UI-Simcor

1. Introduction

In Japan, seismic design was changed after 1995 Kobe earthquake. As seismic load for design was raised in national design code [1], elastic design was not applicable for large earthquake motion. Plastic deformation of members such as bridge pier was accepted to a limited extent. Moreover anti-seismic devices have been widely adopted. These devices have energy dissipation function by using rubber, low-yielding steel and fluid materials. It is expected that plastic deformation of main member of the structure can be reduced by using anti-seismic devices. On the other hand, such devices often have thermal dependencies in low temperature range. Northern Pacific area including Hokkaido and Tohoku of Japan have suffered severe earthquakes in history. Therefore evaluating the performance of anti-seismic devices in cold environment is important for reasonable designing of civil structures.

In modern earthquake engineering research, experiments using shaking tables and numerical calculations are commonly adopted to estimate seismic responses of structures. For large scale structures such as bridges or tall buildings, there are difficulties to use shaking table because of limitation of driving force of actuators. On the other hand, numerical calculation technique have been developed in these 20 years and useful software for designing is available. In such software material nonlinearity is considered to calculate post yielding response of members. However, there is still room for improvement to evaluate more real and more complex situation of actual structure such as thermal dependency of seismic devices.

In such cases, hybrid simulation which combine numerical simulation and structural experiment is effective method and it have been researched for years [2], [3]. In these hybrid simulation scheme, sub-structuring is also commonly adopted [4]. The concept of hybrid simulation was proposed in 1960's by Hakuno [5] and many researches have performed. In 2000's, George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) Program started in United States. An open-source software for distributed hybrid pseudo-dynamic simulation have been developed and provided for researchers and engineers as one of the outcome of the program [6], [7].

In this study, the authors developed substructured hybrid simulation system in cold room by updating an existing loading facilities [8]. UI-Simcor [6] was adopted as the core system of the hybrid simulation system because of flexibility of system development. For numerical calculation of substructures, a module program was developed to communicate with a general purpose structural analysis software TDAPIII [9] which is commonly used in Japan.

One simple beam structure with anti-seismic damper was modeled to evaluate validity of developed hybrid simulation system. The simple beam was modeled numerically and anti-seismic damper which was well tested in previous research [10] was used for loaded specimen in both normal and cold temperature.

2. Substructured hybrid simulation system

In this study, UI-Simcor [6] which have been developed in University of Illinois at Urbana-Champaign for NEES project was utilized to establish the substructured hybrid simulation system in cold environment. UI-Simcor offers the simulation coordinator (SC) and SC controls hybrid simulation entirely. Users can develop their original loading and/or structural calculation program and these programs can be integrated into the hybrid simulation via control program with a communication protocol. The authors have been developed loading facility in cold room and its control program was developed for this hybrid simulation. For calculation of static response of structure, TDAP III [9] which is a general commercial FEM software was adopted because the software offers operation with a command prompt window. A control program to use the FEM software in the hybrid simulation was also developed in this study. The system configuration in this study is shown in Fig. 1.

In the component 1, static analysis of the structural model was performed. Input data file of TDAP III was generated based on ordered displacement from SC. Then, static response analysis was performed in TDAP III. Section force of each member were loaded from its output data file and these section force were transferred to restoring force in each nodal point and were sent to SC with response displacement of the node. This procedure were repeated until end of the hybrid simulation.

In the component 2, loading test for the specimen was performed using a dynamic actuator. The position of actuator was moved based on ordered displacement from SC and displacement and load of the actuator were measured. The position of the actuator was changed immediately after acquiring data from SC. However operational speed of the actuator is slower than simulation system. Therefore the measurement of displacement and load should be done after the actuator's operation. On the other hand, in the case of energy dissipation device like a seismic damper, load of actuator was decreased in this stopping time. In this study the stopping time was optimized by preliminary tests [8].

The α-Operator Splitting (α-OS) time integration technique was adopted in UI-Simcor [11]-[13]. In the α-OS method, stiffness of the structure is divided into a linear subpart and a nonlinear subpart. The explicit

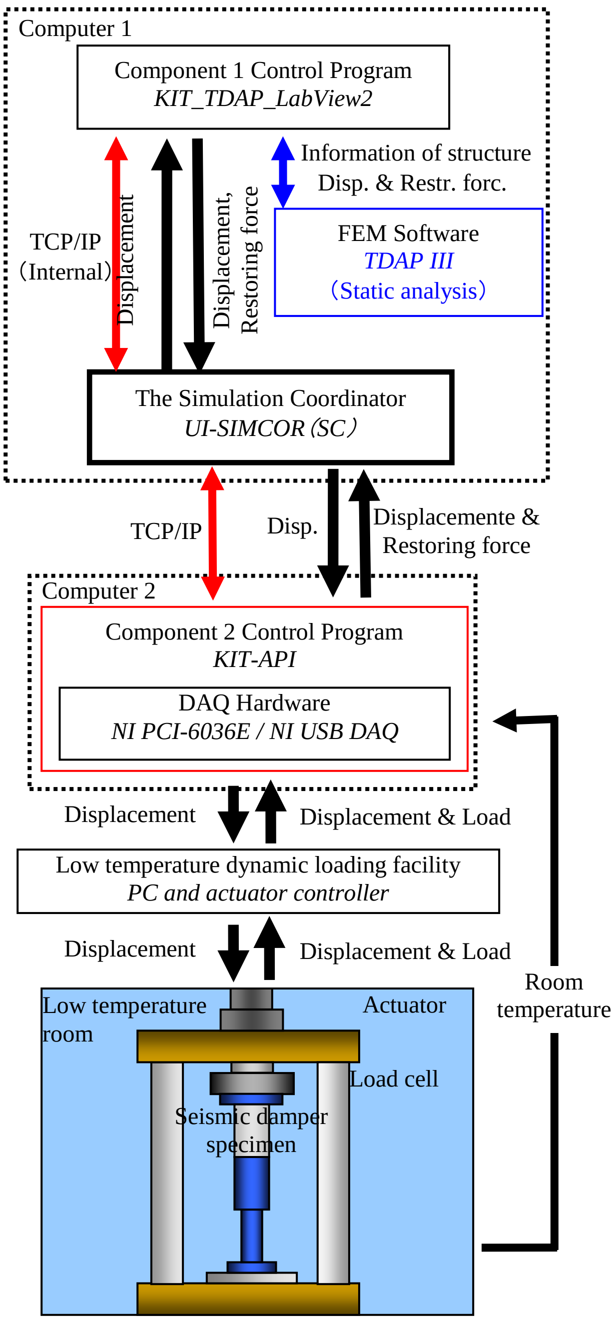


Fig. 1 System configurartion

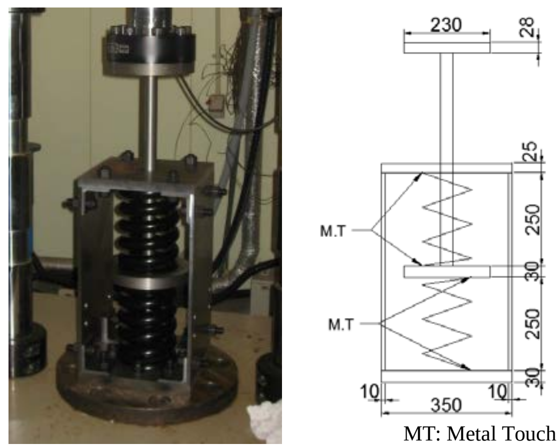


Fig.2 Linear spring specimem

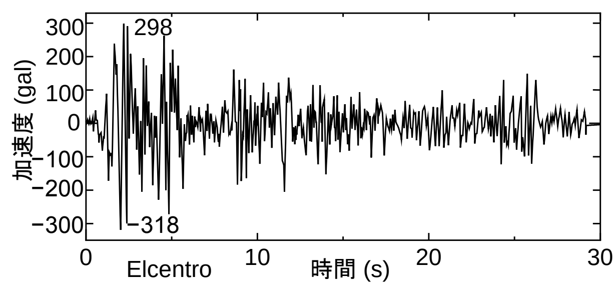


Fig. 3 Input excitation wave

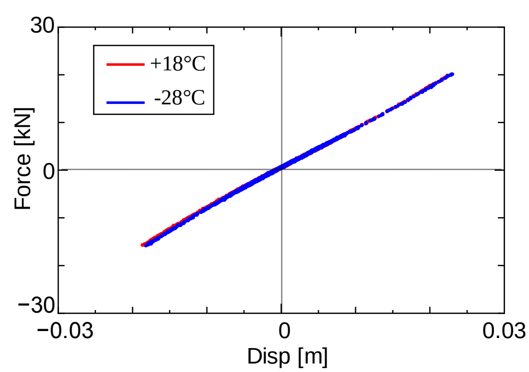


Fig. 4 Displacement - load relationship of the sping specimen

predictor-corrector method is employed for integrations for the nonlinear stiffness. The α methods is employed for integration for the linear stiffness [11]. Actual process for numerical integration is shown in the reference [13].

3. Hybrid simulation with linear spring specimen

In this study, feasibility of the system was examined by using 1DOF model with linear spring specimen [8]. The spring specimen is shown in Fig. 2 and the specimen has 2 compression springs to obtain same restoring force in both tension and compression direction in the simulation. Stiffness of spring was 874kN/m and numerical mass of 1DOF model was 25x10^3 kg.

For α-OS method of hybrid simulation, the parameter α was set to α=0.0 because this 1DOF system is linear. Therefore β=0.25 and γ=0.50, this setting is equivalent to the Newmark β integration method. Time interval was Δt=0.01 sec and the simulation time was 30 seconds. Input excitation wave was shown in Fig. 3 which is the earthquake record at El Centro in 1940. Stopping time for actuator as mentioned above was 0.1 sec for preliminary tests. The hybrid simulations were performed in 2 room temperature settings: -28 °C and 18 °C.

Fig. 4 is the displacement - load relationship of the spring specimen in both cold and normal temperature. The spring was reasonably linear and it did not has thermal dependency. Therefore this hybrid simulation system can operate properly in cold environment.

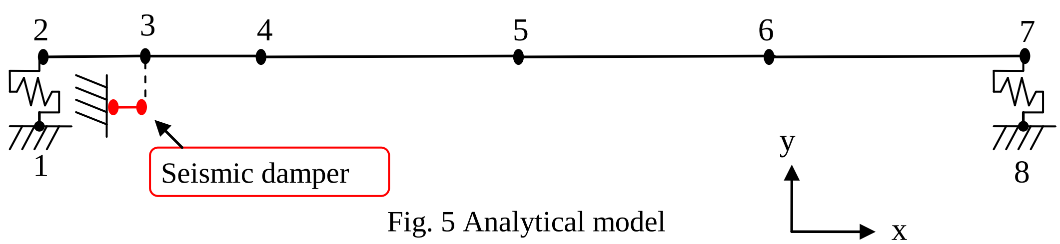


Fig. 5 Analytical model

Table 1. Node coordinate [m]

Node #	x	y
1	0.0	0.0
2	0.0	1.0
3	5.0	1.0
4	10.0	1.0
5	20.0	1.0
6	30.0	1.0
7	40.0	1.0
8	40.0	0.0

Table 2. Node mass [kg]

Node #	Mass
2	15.70×10^3
3	15.70×10^3
4 - 7	23.55×10^3

Table 3. Section properties

Member	Section area A [m^2]	Morment of inertia I [m^4]
Main girder	0.12	0.19×10^{-3}
Spring support	Spring constatn (axial direction) 1.64×10^3 kN/m	

4. Hybrid simulation of simple girder model with seismic damper

Fig. 5 shows the analytical model of a simple girder with a seismic damper. The 40m simple beam was supported by spring supports and a seismic damper was equipped at the end of girder. An actual seismic damper was employed for the test specimen. The rest of analytical model was established as a numerical model for the

Fig.6 Seismic damper specimen

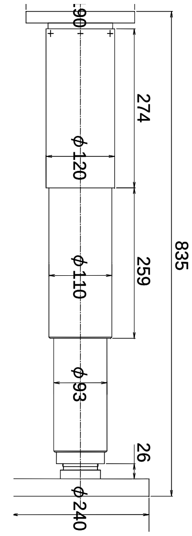
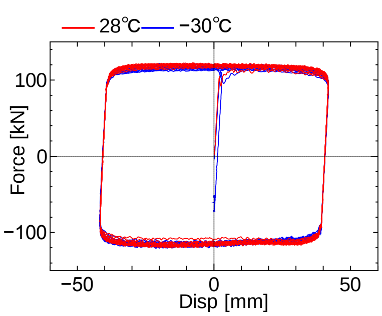


Fig.7 Dimension of the specimem



Sinusoidal loading at 0.1Hz [13]

Fig. 8 Histerisis loop of the damper

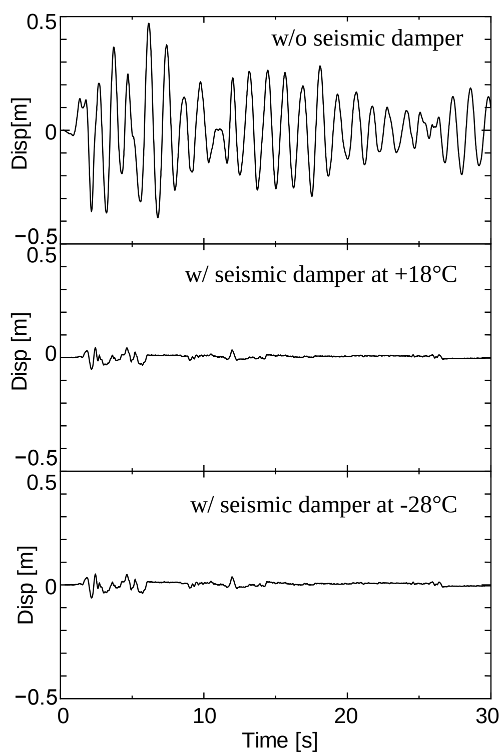


Fig. 9 Time history displacement at node 3

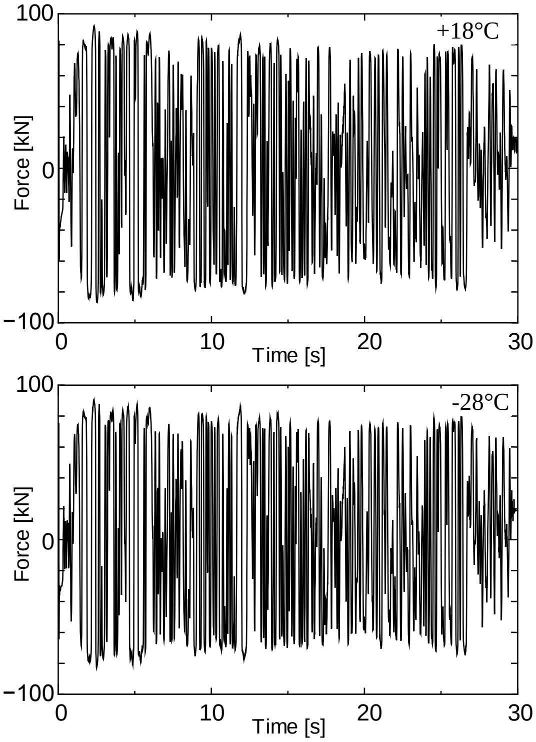


Fig.10 Time hisotry load of the seismic damper

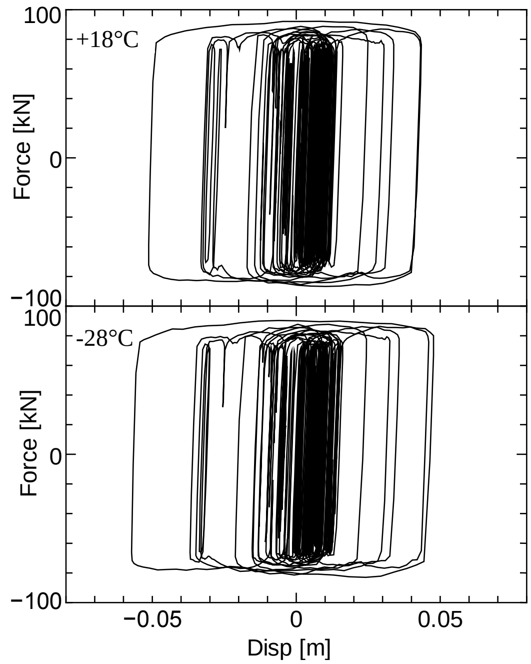


Fig.11 Histerisis loop of the seismic damper

general FEM software.

Node numbers of the model are shown in Fig. 5 and Table 1 shows their coordinates. This model was a 2-dimentional model and excitation wave was input to the bridge axial direction to examine the performance of a seismic damper. The seismic damper was connected to node #3 in Fig. 5. Node masses of the girder are shown in Table 2 and its section properties are shown in Table 3. Eigenvalue analysis was performed preliminary and fundamental natural frequency was 0.81 Hz. Damping ratio was set 0.05 at the fundamental frequency.

A Bingham stopper for bridges (BM-S, OILES Corp.) as shown in Figs. 6 and 7 was employed for the seismic damper. Mass of the damper was 50 kg, the maximum stroke was 100 mm and the resistance force was 150 kN at 0.5m/sec. This seismic device uses Bingham material in its cylinder and the resistance force and displacement shows a rectangular friction hysteresis type. To obtain basic characteristics of the device under low temperature, cyclic loading test was performed in reference [10] and one of the results is shown in Fig. 8. The resistance force did not change between normal temperature and lower temperature because of both characteristics of Bingham material and an innovative mechanism of the cylinder.

For the parameters in α-OS method of hybrid simulation, α was set to α=-0.25 considering stability of simulation. Therefore β=0.39 and γ=0.75 were adopted. Time interval was Δt=0.01 sec and the simulation time was 30 seconds. Input excitation wave was shown in Fig. 3. Stopping time for actuator was 0.5 sec for preliminary tests with the seismic damper. The hybrid simulations were performed in 2 room temperature settings: -28 °C and 18 °C. Moreover, numerical simulation without seismic damper was also performed to evaluate the effect of seismic damper.

Fig. 9 shows time history displacement at node #3 in each case; without the seismic damper, with the seismic damper in 18 °C and -28 °C. Fig. 10 shows time history load of the seismic damper in 18 °C and -28 °C. Fig. 11 shows load-displacement relationship of the damper.

In the upper figure of Fig. 9, the response displacement of the girder increased by excitation and that corresponded to input excitation wave as shown in Fig. 3. In the middle and bottom figures of Fig. 9, response displacement was reduced 80% by energy dissipation effect of the seismic damper. This energy dissipation effect were observed in both experimental cases in 18 °C and -28 °C. Time history load of the damper shown in Fig. 10 reached resistance force in design and that demonstrated this seismic damper work efficiently over simulation time. The seismic damper showed friction type hysteresis loop from the load – displacement relationship shown in Fig. 11. These results were corresponded to fundamental test result shown in Fig. 8. And the differences of temperature was quite small.

In detailed discussion of hybrid simulation system from Fig. 11, resistance force varied in the upper and bottom side of hysteresis loop. The reason of this fluctuation was stopping time of the system for waiting the actuator's operation in each time step of the simulation. This hybrid simulation algorithm was established based on the idea of pseudo dynamic testing. As for further study, real time loading test need to be developed for such energy dissipation devices.

From above results, hybrid simulation system obtains dynamic response of structure under low temperature environment and a general commercial software can be used for convenience of users.

5. Conclusion

In this study, the substructured hybrid simulation system in cold room was developed to evaluate performance of large scale structure with anti-seismic devices in cold environment. The UI-Simcor was adopted as the core system of the hybrid simulation system and a module program was developed to communicate with a general purpose structural analysis software. And sub-program which could cooperate with existent loading facility in a cold room was also developed.

A simulation for a simple girder model with a seismic damper was performed. The girder was modeled by a general FEM software. A seismic device was connected to an intermediate node of the girder model. This seismic device was an experimental part of the hybrid simulation system. To confirm working the system properly, linear steel springs were installed instead of a seismic damper. Then after the pretest, a seismic damper was installed to evaluate seismic performance of the whole structure.

In the hybrid simulation, dynamic response of the damper was obtained as a part of whole structure and friction type displacement-force hysteresis curve was properly obtained. The maximum displacement was considerable reduced by energy dissipation of the damper. The system was able to work properly as a substructured hybrid simulation facility at a low-temperature environment. Both stiffness and hysteric damping performance of the damper were not affected by low temperature. This stable characteristics of the damper have been verified in basic sinusoidal excitation tests in previous studies. In this study, actual performance for seismic excitation under low temperature was confirmed by the hybrid simulation. From above results, hybrid simulation system obtains dynamic response of structure under low temperature environment and a general commercial software can be used for convenience of users.

For further studies, in the hysteresis loop of seismic damper in hybrid simulation, maximum force of the damper fluctuated by energy dissipation during stopping time of actuator. To avoid this phenomena real time hybrid simulation needs to be developed as future works.

Acknowledgements

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